$t \to bWh^0$ and $t \to bWA^0$ decays and possible CP violating effects.

E. O. Iltan *

Physics Department, Middle East Technical University

Ankara, Turkey

Abstract

We study the charged $t \to bWh^0$ and $t \to bWA^0$ decays in the framework of the general two Higgs doublet model, so called model III and beyond. Here, we take the Yukawa couplings complex and introduce a new complex parameter due to the physics beyond the model III, to switch on the CP violating effects. We predict the branching ratios as $BR(t \to bWh^0) \sim 10^{-6}$ and $BR(t \to bWA^0) \sim 10^{-8}$. Furthermore, we observe a measurable CP asymmetry, at the order of 10^{-2}, for both decays.

*E-mail address: eiltan@heraklit.physics.metu.edu.tr

1 Introduction

Because of its large mass, the top quark has rich decay products and this opens a new window to test the standard model (SM) and to get some clues about the new physics, beyond. In the literature there are various studies in the SM and beyond [1]-[13].The rare flavor changing transitions $t \to cg(\gamma, Z)$ have been studied in [4, 6], $t \to cH^0$ in [2, 6, 7, 8, 9] and $t \to cl_1 l_2$ in [10]. The SM predictions of the branching ratio (BR) of the process $t \to cg(\gamma, Z)$ is 4×10^{-11} (5×10^{-13}, 1.3×10^{-13}) [2], and $t \to cH^0$ is at the order of the magnitude of $10^{-14} - 10^{-13}$, in the SM [7], which are not measurable quantities even at the highest luminosity accelerators. Possible new physics effects are the candidates for the enhancement of the BR's of the above processes. $t \to cH^0$ and $t \to cl_1 l_2$ decays have been analysed in [9] and [10], in the framework of the general two Higgs doublet model (model III). In these studies it has been observed that there could be a strong enhancement in the BR, almost seven orders larger compared to the one in the SM for the decay $t \to cH^0$; a measurable BR, at the order of the magnitude of $10^{-8} - 10^{-7}$ for the decay $t \to cl_1 l_2$. In [11] $t \to cVV$ decay has been analysed in the topcolor assisted technicolor theory.

The charged $t \to b$ transitions exist in the SM model and have been studied in the literature extensively. The top decay $t \to bW$ has been analysed (see [12] and references therein) in the two Higgs doublet model and $t \to bWZ$ decay has been studied in [13].

The present work is devoted to the analysis of the charged $t \to b\, W\, h^0$ and $t \to b\, W\, A^0$ decays in the framework of the general two Higgs doublet model (model III). This decay occurs in the tree level with the extended Higgs sector since the scalar bosons h^0 and A^0 exist in the new sector. We study the BR of the above decays and obtain a measurable quantities, at the order of the magnitude of 10^{-6} and 10^{-8}, respectively. Furthermore, we search the possible CP violating effects. To obtain a nonzero CP asymmetry A_{CP} we take Yukawa coupling for $b\, h^0\, (A^0)\, b$ transition complex and introduce a new complex parameter, where its complexity comes from some type of radiative corrections, due to the model beyond the model III (see section II). We obtain a measurable A_{CP}, at the order of the magnitude of 10^{-2} and observe that these physical quantities can give valuable information about physics beyond the SM, the free parameters existing in these models.

The paper is organized as follows: In Section 2, we present the BR and A_{CP} of the decay $t \to b\, W\, h^0 (A^0)$ in the framework of model III. Section 3 is devoted to discussion and our conclusions.

2 $t \rightarrow bWh^0$ and $t \rightarrow bWA^0$ decays with possible CP violating effects.

If one respects the current mass values of $h^0(A^0)$, namely $m_{h^0} \sim 85\, GeV$ ($m_{A^0} \sim 90\, GeV$), the charged $t \rightarrow bWh^0(A^0)$ is kinematically possible and does not exist in the SM model. With the minimal extension of the Higgs sector the CP odd new Higgs scalar A^0 arises and the $t \rightarrow bWA^0$ decay in the tree level is permitted. In this model, $t \rightarrow bWh^0$ decay is possible in the tree level, where h^0 is the new CP even Higgs scalar and, in general, it mixes with the SM one, H^0. In this section, we study the BR in the general two Higgs doublet model, so called model III and the possible CP violating asymmetry, beyond.

The $t \rightarrow bWh^0(A^0)$ decay is created by the charged $t \rightarrow bW$ process and the neutral $t \rightarrow t^* h^0(A^0)$ or $b^* \rightarrow bh^0(A^0)$ processes, which are controlled by the Yukawa interaction

$$\mathcal{L}_Y = \eta^U_{ij} \bar{Q}_{iL} \tilde{\phi}_1 U_{jR} + \eta^D_{ij} \bar{Q}_{iL} \phi_1 D_{jR} + \xi^{U\,\dagger}_{ij} \bar{Q}_{iL} \tilde{\phi}_2 U_{jR} + \xi^D_{ij} \bar{Q}_{iL} \phi_2 D_{jR} + h.c. \;, \tag{1}$$

where L and R denote chiral projections $L(R) = 1/2(1 \mp \gamma_5)$, ϕ_i for $i = 1, 2$, are the two scalar doublets, $\bar{Q}_{iL}$ are left handed quark doublets, $U_{jR}(D_{jR})$ are right handed up (down) quark singlets, with family indices i, j. The Yukawa matrices $\eta^{U,D}_{ij}$ and $\xi^{U,D}_{ij}$ have in general complex entries. By considering the gauge and CP invariant Higgs potential which spontaneously breaks $SU(2) \times U(1)$ down to $U(1)$ as

$$\begin{aligned} V(\phi_1, \phi_2) &= c_1(\phi_1^+ \phi_1 - v^2/2)^2 + c_2(\phi_2^+ \phi_2)^2 \\ &+ +c_3[(\phi_1^+ \phi_1 - v^2/2) + \phi_2^+ \phi_2]^2 + c_4[(\phi_1^+ \phi_1)(\phi_2^+ \phi_2) - (\phi_1^+ \phi_2)(\phi_2^+ \phi_1)] \\ &+ c_5[Re(\phi_1^+ \phi_2)]^2 + c_6[Im(\phi_1^+ \phi_2)]^2 + c_7 \;. \end{aligned} \tag{2}$$

and choosing the parametrization for ϕ_1 and ϕ_2 as

$$\phi_1 = \frac{1}{\sqrt{2}} \left[\left(\begin{array}{c} 0 \\ v + H^0 \end{array} \right) + \left(\begin{array}{c} \sqrt{2} \chi^+ \\ i \chi^0 \end{array} \right) \right] ; \phi_2 = \frac{1}{\sqrt{2}} \left(\begin{array}{c} \sqrt{2} H^+ \\ H_1 + i H_2 \end{array} \right) \;. \tag{3}$$

with the vacuum expectation values,

$$< \phi_1 > = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v \end{array} \right) \; ; < \phi_2 > = 0 \;, \tag{4}$$

the H_1 and H_2 becomes the mass eigenstates h^0 and A^0 respectively since no mixing occurs between two CP-even neutral bosons H^0 and h^0, in tree level. This scenerio permits one to collect SM particles in the first doublet and new particles in the second one. Furthermore the Flavor Changing (FC) interaction can be obtained as

$$\mathcal{L}_{Y,FC} = \xi^{U\,\dagger}_{ij} \bar{Q}_{iL} \tilde{\phi}_2 U_{jR} + \xi^D_{ij} \bar{Q}_{iL} \phi_2 D_{jR} + h.c. \;, \tag{5}$$

with the couplings $\xi^{U,D}$ for the FC charged interactions

$$\begin{aligned}\xi^{U}_{ch} &= \xi^{U}_{N}\, V_{CKM}\ , \\ \xi^{D}_{ch} &= V_{CKM}\, \xi^{D}_{N}\ ,\end{aligned} \tag{6}$$

where $\xi^{U,D}_{N}$ is defined by the expression

$$\xi^{U(D)}_{N} = (V^{U(D)}_{R(L)})^{-1} \xi^{U,(D)} V^{U(D)}_{L(R)}\ . \tag{7}$$

Notice that the index "N" in $\xi^{U,D}_{N}$ denotes the word "neutral".

Using the relevant diagrams for the $t \to bWh^0(A^0)$ decay which are given in Fig 1 and taking into account only the real Yukawa couplings $\xi^{D}_{N,bb}$, $\xi^{U}_{N,tt}$, the matrix element square $|M|^2(h^0)$ ($|M|^2(A^0)$) reads

$$|M|^2_{h^0\,(A^0)}(p1,p_b,k,q) = \xi^{D}_{N,bb}\,\xi^{U}_{N,tt}\, f_1(h^0\,(A^0)) + (\xi^{D}_{N,bb})^2\ f_2(h^0\,(A^0)) + (\xi^{U}_{N,tt})^2\ f_3(h^0\,(A^0)) \tag{8}$$

where

$$\begin{aligned}
f_1(h^0) &= 16\,|V_{tb}|^2\, m_b\, m_t \Bigg(m_W^2 \Big(s_2^2(h^0) - s_1^2(h^0) + 2\,s_1(h^0)\,s_2(h^0)\Big) x_{h^0} \\
&+ 2\,s_1(h^0)\,\Big((s_1(h^0) - s_2(h^0))\,k.(p_1 - p_b) + 2\,s_1(h^0)\,p_1.p_b\Big) \\
&+ \frac{1}{m_W^2}\,\Big(- (s_2^2(h^0) + 2\,s_1^2(h^0) + 2\,s_1(h^0)\,s_2(h^0))\,(k.q)^2 + 2\,s_1(h^0)\,(2\,s_1(h^0) \\
&+ s_2(h^0))\,k.q\,q.(p_1 - p_b) + 8\,s_1^2(h^0)\,p_1.q\,p_b.q\Big)\Bigg)\ , \\
f_2(h^0) &= 8\,|V_{tb}|^2 \Bigg(- m_W^2 \Big(s_2(h^0) + s_1(h^0)\Big)^2 x_{h^0}\,p_1.p_b \\
&+ \frac{1}{m_W^2}\,k.q\,\Big((s_2(h^0) + 2\,s_1(h^0)) \\
&\times\ (s_2(h^0)\,k.q\,p_1.p_b + 2\,s_1(h^0)\,k.p_b\,q.p_1) - 2\,s_1(h^0)\,s_2(h^0)\,k.p_1\,p_b.q\Big) \\
&+ 2\,s_1^2(h^0)\,(k.p_1\,k.p_b - x_{h^0}\,q.p_1\,q.p_b)\Bigg)\ , \\
f_3(h^0) &= 8\,|V_{tb}|^2 \Bigg(- m_W^2 \Big(4\,s_1(h^0)\,(s_1(h^0) - s_2(h^0))\,x_t\,k.p_b + \Big((s_1(h^0) + s_2(h^0))^2\,x_{h^0} \\
&- 4\,s_1^2(h^0)\,x_t\Big)\,p_1.p_b\Big) \\
&+ \frac{1}{m_W^2}\,k.q\,\Big(s_2(h^0)\,(s_2(h^0) + 2\,s_1(h^0))\,k.q\,p_1.p_b - 2\,s_1(h^0)\,s_2(h^0)\,q.p_1\,k.p_b + 2\,s_1(h^0) \\
&\times\ (2\,s_1(h^0) + s_2(h^0))\,k.p_1\,q.p_b\Big) \\
&+ 2\,s_1(h^0)\,\Big(s_1(h^0)\,k.p_1\,k.p_b - \Big(2\,(2\,s_1(h^0) + s_2(h^0))\,x_t\,k.q + s_1(h^0)\,(x_{h^0} - 4\,x_t)\,q.p_1\Big)\,q.p_b\Big)\Bigg)\ ,
\end{aligned}$$

$$
\begin{aligned}
f_1(A^0) &= 16\,|V_{tb}|^2\, m_b\, m_t \left(m_W^2 \Big(s_2^2(A^0) + s_1^2(A^0)\Big)\, x_{A^0} + \frac{1}{m_W^2} \Big(2\, s_1^2(A^0) - s_2^2(A^0)\Big)\, (k.q)^2 \right), \\
f_2(A^0) &= 8\,|V_{tb}|^2 \Bigg(- m_W^2 \Big(s_2(A^0) + s_1(A^0)\Big)^2 x_{A^0}\, p_1.p_b \\
&+ \frac{1}{m_W^2}\, k.q\, \Big((s_2(A^0) + 2\, s_1(A^0))\, (s_2(A^0)\, k.q\, p_1.p_b + 2\, s_1(A^0)\, k.p_b\, p_1.q) \\
&- 2\, s_1(A^0)\, s_2(A^0)\, k.p_1\, p_b.q \Big) + 2\, s_1^2(A^0)\, (k.p_1\, k.p_b - x_{A^0}\, q.p_1\, q.p_b) \Bigg), \\
f_3(A^0) &= 8\,|V_{tb}|^2 \Bigg(- m_W^2 \Big(s_1(h^0) - s_2(h^0)\Big)^2 x_{A^0}\, p_1.p_b \\
&+ \frac{1}{m_W^2}\, k.q\, \Big(s_2(A^0)\, (s_2(h^0) - 2\, s_1(h^0))\, k.q\, p_1.p_b + 2\, s_1(A^0)\, (2\, s_1(A^0) - s_2(A^0))\, k.p_1\, p_b.q \\
&+ 2\, s_1(A^0)\, s_2(A^0)\, k.p_b\, p_1.q \Big) + 2\, s_1^2(A^0) \Big(k.p_1\, k.p_b - x_{A^0}\, p_1.q\, p_b.q \Big) \Bigg). \qquad (9)
\end{aligned}
$$

Here the functions $s_{1(2,3)}(h^0(A^0))$ are

$$
\begin{aligned}
s_1(h^0) &= -\frac{g_W}{4\, m_W^2\, (1 + x_t - 2\, \frac{p_1.q}{m_W^2})}, \\
s_2(h^0) &= \frac{g_W}{2\, m_W^2\, (1 + x_{h^0} - y_t - 2\, \frac{k.q}{m_W^2})}, \\
s_{1(2)}(A^0) &= (-)\, s_{1(2)}(h^0 \to A^0), \qquad (10)
\end{aligned}
$$

with weak coupling constant g_W, $x_{h^0(A^0)} = \frac{m^2_{h^0(A^0)}}{m_W^2}$, $x_t = \frac{m_t^2}{m_W^2}$ and $y_t = \frac{m^2_{H^\pm}}{m_W^2}$ and p_1, p_b, q and k are four momentum of t quark, b quark, W boson and Higgs scalar $h^0(A^0)$, respectively.

Finally, using the well known expression defined in the t quark rest frame

$$
\begin{aligned}
d\Gamma_{h^0\,(A^0)} &= \frac{(2\pi)^4}{12\, m_t}\, \delta^{(4)}(p_1 - p_b - k - q)\, \frac{d^3 p_b}{(2\pi)^3\, 2\, E_b}\, \frac{d^3 q}{(2\pi)^3\, 2\, E_W}\, \frac{d^3 k}{(2\pi)^3\, 2\, E_{h^0(A^0)}} \\
&\times\ |M|^2_{h^0\,(A^0)}(p_1, p_b, k, q) \qquad (11)
\end{aligned}
$$

and the total decay width $\Gamma_T \sim \Gamma(t \to bW)$ as $\Gamma_T = 1.55\, GeV$, we get the BR for the decay $t \to bW h^0(A^0)$.

Now, we would like to study a possible CP violating effects, which can give comprehensive information about the free parameters of the model used. For the process under consideration, the CP violation can be obtained by choosing the complex Yukawa couplings in general, namely, taking the parametrizations

$$
\begin{aligned}
\xi^U_{N,tt} &= |\xi^U_{N,tt}|\, e^{i\theta_{tt}}, \\
\xi^D_{N,bb} &= |\xi^D_{N,bb}|\, e^{i\theta_{tb}}. \qquad (12)
\end{aligned}
$$

However, this choice is not enough to get non-zero A_{CP}

$$A_{CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \tag{13}$$

where $\bar{\Gamma}$ is the decay width for the CP conjugate process. This forces one to go beyond the model III and try to obtain a new complex quantity so that its complexity does not come from the Yukawa couplings but from some radiative corrections. Under the light of this discussion, we introduce an additional complex correction χ to $b \to b$ transition, which may come from the new model beyond the model III as

$$\begin{aligned} &(\xi^D_{N,bb} + \xi^{D*}_{N,bb}) \;\; + \;\; (\xi^D_{N,bb} - \xi^{D*}_{N,bb})\gamma_5 + \chi \\ &\qquad\qquad\qquad \text{and} \\ &(\xi^{D*}_{N,bb} - \xi^D_{N,bb}) \;\; - \;\; (\xi^D_{N,bb} + \xi^{D*}_{N,bb})\gamma_5 + \chi\gamma_5 \, , \end{aligned}$$

Here we take the magnitude of χ at most $|\chi| \sim 10^{-2}$, which is more than one order smaller compared to the vertex due to model III. In this case, we take the correction to the $t \to t$ transition small since the strength of $t \to t$ transition is weaker compared to strength of the $b \to b$ transition, with respect to our choice (see Discussion section).

At this stage, we introduce a model beyond the model III as follows: The multi Higgs doublet model which contains more than two Higgs doublets in the Higgs sector can be one of the candidate. The choice of three Higgs doublets brings new Yukawa couplings which are responsible with the interactions between new Higgs particles and the fermions. The Yukawa lagrangian in three Higgs doublet model (3HDM) reads

$$\begin{aligned} \mathcal{L}_Y &= \eta^U_{ij} \bar{Q}_{iL} \tilde{\phi}_1 U_{jR} + \eta^D_{ij} \bar{Q}_{iL} \phi_1 D_{jR} + \xi^{U\,\dagger}_{ij} \bar{Q}_{iL} \tilde{\phi}_2 U_{jR} + \xi^D_{ij} \bar{Q}_{iL} \phi_2 D_{jR} + \rho^U_{ij} \bar{Q}_{iL} \tilde{\phi}_3 U_{jR} \\ &+ \rho^D_{ij} \bar{Q}_{iL} \phi_3 D_{jR} + h.c. \;\; , \end{aligned} \tag{14}$$

where $\rho^{U(D)}_{ij}$ is the new coupling and ϕ_3 can be chosen as

$$\phi_3 = \frac{1}{\sqrt{2}} \left(\begin{array}{c} \sqrt{2} F^+ \\ H_3 + i H_4 \end{array} \right) \; , \tag{15}$$

with vanishing vacuum expectation value. The fields F^+ and H_3 (H_4) represent the new charged and CP even (odd) Higgs particles, respectively. Notice that the other Yukawa couplings and Higgs particles in eq. (14) are the ones existing in the model III. Now, we choose the additional Yukawa couplings $\rho^{U(D)}_{ij}$ real and take into account the radiative corrections to the $b \to b$ transition which comes from the contributions of third Higgs doublet for the decay under consideration. Here the complexity of the parameter should come from the radiative corrections but not from the new Yukawa couplings. We can take this complex contribution as a source for the additional part χ. Since the number of free parameters, namely masses of new Higgs particles $m_{F^\pm}$, m_{H_3}, m_{H_4} and the new Yukawa couplings $\rho^{U(D)}_{ij}$, increases, there arises a difficulty to restrict them. However, the overall uncertainity coming from these free parameters lies in the contribution χ and it can be overcome by the possible future measurement of the CP violation for our process.

Finally, by using the definition

$$A_{CP}^{h^0(A^0)}(E_W,E_b)=\frac{\frac{d^2\Gamma(t\rightarrow bWh^0(A^0))}{dE_b dE_W}-\frac{d^2\Gamma(\bar{t}\rightarrow \bar{b}\bar{W}h^0(A^0))}{dE_b dE_W}}{\frac{d^2\Gamma(t\rightarrow bWh^0(A^0))}{dE_b dE_W}+\frac{d^2\Gamma(\bar{t}\rightarrow \bar{b}\bar{W}h^0(A^0))}{dE_b dE_W}} \tag{16}$$

we obtain the differential $A_{CP}(E_W,E_b)$ for the process $t\rightarrow bWh^0(A^0)$ as

$$A_{CP}^{h^0(A^0)}(E_W,E_b) \;=\; |\bar{\xi}^D_{N,bb}|\,|\chi|\,sin\theta_{bb}\,sin\theta_\chi \frac{\Phi^{h^0(A^0)}}{D^{h^0(A^0)}}\,, \tag{17}$$

where

$$\begin{aligned}
\Phi^{h^0} &= 4\,m_t\,s_1(h^0)\,|V_{tb}|^2\Bigg(4\Big(2\,E_W^2\,m_t\,s_1(h^0)\,(x_t-2)-E_b^2\,(2\,E_W+m_t)\,s_2(h^0)\,(1+x_t)\\
&+ E_b\,E_W\Big(E_W(s_2(h^0)(1+3\,x_{h^0}-3\,x_t)+4\,s_1(h^0)(1+2\,x_{h^0}))\\
&+ m_t\,(s_2(h^0)+2\,s_1(h^0)\,(2\,x_{h^0}+x_t))\Big)\Big)\\
&+ m_W^2\Big(m_t(s_2(h^0)\,(-1+(x_{h^0}-x_t)^2)+4\,s_1(h^0)\,(1+x_t+x_{h^0})+2\,E_b\,(-2\,s_1(h^0)\,(1+2\,x_{h^0}+x_t)\\
&+ s_2(h^0)\,(-1+x_{h^0}-x_t)\,(2\,x_t-1))\\
&- 2\,E_W\,(s_2(h^0)\,(x_{h^0}-x_t)\,(1-x_t+x_{h^0})+s_1(h^0)\,(4+2\,x_{h^0}\,(2+2\,x_{h^0}-x_t)+2\,x_t\,(3-x_t)))\Big)\\
&+ \frac{8}{m_W^2}\,\Big(E_b\,E_W^2\,(E_b(2\,E_W+m_t)\,s_2(h^0)-4\,E_W\,m_t\,s_1(h^0))\Big)\Bigg)\,,\\
\Phi^{A^0} &= 4\,m_t\,s_1(A^0)\,|V_{tb}|^2\Bigg(4\Big(2\,E_W^2\,m_t\,s_1(A^0)\,(x_t-2)-E_b^2\,(2\,E_W+m_t)\,s_2(A^0)\,(1+x_t)\\
&+ E_b\,E_W\Big(E_W(s_2(A^0)(1+3\,x_{A^0}-3\,x_t)+4\,s_1(A^0)(1+2\,x_{A^0}))\\
&+ m_t\,(s_2(A^0)+2\,s_1(A^0)\,(2\,x_{A^0}+x_t))\Big)\Big)\\
&+ m_W^2\Big(-m_t(s_2(A^0)\,(-1+(x_{A^0}-x_t)^2)+4\,s_1 A^0\,(1+x_t+x_{A^0})\\
&+ 2\,E_b\,(2\,s_1(A^0)\,(1+2\,x_{A^0}+x_t)+s_2(A^0)\,(-1+x_t+2\,x_t^2+x_{A^0}(1-2\,x_t))\\
&+ 2\,E_W\,\Big(s_2(A^0)\,(x_{A^0}-x_t)\,(1-x_t+x_{A^0})+s_1(A^0)\,(4+4\,x_{A^0}\,(1+x_{A^0}-2\,x_t)+2\,x_t\,(3-x_t))\Big)\Big)\\
&+ \frac{8}{m_W^2}\,\Big(E_b\,E_W^2\,(E_b(2\,E_W+m_t)\,s_2(A^0)-4\,E_W\,m_t\,s_1(A^0))\Big)\Bigg)\,,
\end{aligned} \tag{18}$$

with $\chi = e^{i\,\theta_\chi}\,|\chi|$, $\bar{\xi}^{D}_{N,bb} = e^{i\,\theta_{bb}}\,|\bar{\xi}^{D}_{N,bb}|$. Notice that we do not present the functions $D(h^0)$ and $D(A^0)$ since their explicit expressions are long. Here the functions $s_1(h^0(A^0))$ and $s_2(h^0(A^0))$ are given in eq.(10).

3 Discussion

This section is devoted to the analysis of the BR and A_{CP} of the decay $t \to bWh^0$ and $t \to bWA^0$ in the framework of model III and beyond. In our numerical analysis we use the form of the coupling $\bar{\xi}^{U(D)}_{N,ij}$, which is defined as $\xi^{U(D)}_{N,ij} = \sqrt{\frac{4\,G_F}{\sqrt{2}}}\,\bar{\xi}^{U(D)}_{N,ij}$.

Since the model III contains large number of free parameters such as Yukawa couplings, $\bar{\xi}^{U(D)}_{N,ij}$, the masses of new Higgs bosons, $H^\pm$, h^0 and A^0, we try to restrict them by using experimental measurements. In our calculations, we neglect all the Yukawa couplings except $\bar{\xi}^{U}_{N,tt}$ and $\bar{\xi}^{D}_{N,bb}$, due to their their light flavor contents. In addition to this we neglect the off diagonal coupling $\bar{\xi}^{U}_{N,tc}$, since it is smaller compared to $\bar{\xi}^{U}_{N,tt}$ (see [14]). One of the most important experimental measurement for the prediction of the constraint region for the couplings $\bar{\xi}^{U}_{N,tt}$ and $\bar{\xi}^{D}_{N,bb}$ is the the CLEO measurement [15]

$$BR(B \to X_s\gamma) = (3.15 \pm 0.35 \pm 0.32)\,10^{-4}\ . \tag{19}$$

and our procedure is to restrict the Wilson coefficient C_7^{eff} which is the effective coefficient of the operator $O_7 = \frac{e}{16\pi^2}\bar{s}_\alpha\sigma_{\mu\nu}(m_b R + m_s L)b_\alpha\mathcal{F}^{\mu\nu}$ (see [14] and references therein), in the region $0.257 \leq |C_7^{eff}| \leq 0.439$, where the upper and lower limits were calculated using eq. (19) and all possible uncertainities in the calculation of C_7^{eff} [14]. In the case of the calculation of A_{CP}, $\bar{\xi}^{D}_{N,bb}$ ($\bar{\xi}^{U}_{N,tt}$) is taken complex (real) and a new small complex parameter χ, due to the physics beyond model III, is introduced. In the following, we choose $|r_{tb}| = |\frac{\bar{\xi}^{U}_{N,tt}}{\bar{\xi}^{D}_{N,bb}}| < 1$. Notice that, in figures, the BR and A_{CP} are restricted in the region between solid (dashed) lines for $C_7^{eff} > 0$ ($C_7^{eff} < 0$). Here, there are two possible solutions for C_7^{eff} due to the cases where $|r_{tb}| < 1$ and $r_{tb} > 1$. In the case of complex Yukawa couplings, only the solutions obeying $|r_{tb}| < 1$ exist.

In Fig. 2, we plot the $BR(t \to bWh^0)$ with respect to $\frac{\bar{\xi}^{D}_{N,bb}}{m_b}$ for $m_{H^\pm} = 400\,GeV$, $m_{h^0} = 85\,GeV$. As shown in this figure, the BR is at the order of the magnitude of 10^{-6} and it increases with the increasing values of the $\frac{\bar{\xi}^{D}_{N,bb}}{m_b}$. Its magnitude (the restriction region) is larger (broader) for $C_7^{eff} > 0$ compared to the one for $C_7^{eff} < 0$.

Fig. 3 is devoted to the same dependence of the $BR(t \to bWA^0)$ for $m_{H^\pm} = 400\,GeV$, $m_{A^0} = 90\,GeV$. For this process the BR is at the order of the magnitude of 10^{-8}, almost 2 order smaller compared to the $BR(t \to bWh^0)$. It increases with the increasing values of the

$\frac{\bar{\xi}^{D}_{N,bb}}{m_b}$ and its magnitude (the restriction region) is larger (broader) for $C_7^{eff} > 0$ compared to the one for $C_7^{eff} < 0$. Furthermore, the restriction region is sensitive to the parameter $\frac{\bar{\xi}^{D}_{N,bb}}{m_b}$ and for $C_7^{eff} < 0$, upper and lower bounds almost coincide.

Fig. 4 (5) represents $BR(t \rightarrow bWh^0(A^0))$ with respect to $m_{h^0}(m_{A^0})$ for $m_{H^\pm} = 400\, GeV$ and $\bar{\xi}^{D}_{N,bb} = 30\, m_b$. Here the BR increases with the decreasing values of $m_{h^0}(m_{A^0})$. This can give a powerfull information about the lower limit of the mass value $m_{h^0}(m_{A^0})$ with the help of the possible future experimental measurement of the process under consideration. Notice that with the increasing values of $m_{h^0}(m_{A^0})$ the restriction regions for $C_7^{eff} > 0$ and $C_7^{eff} < 0$ become narrower and coincide.

Now, we would like to analyse the CP asymmetry A_{CP} of the decay $t \rightarrow bWh^0(A^0)$. To obtain a nonzero A_{CP} we take the coupling $\bar{\xi}^{D}_{N,bb}$ complex and introduce a new complex parameter χ due to the physics beyond the model III (see section II).

In Fig 6 (7) we present the $sin\, \theta_{bb}$ dependence of $A_{CP}(t \rightarrow bWh^0(A^0))$ for $|\bar{\xi}^{D}_{N,bb}| = 30\, m_b$, $|\chi| = 10^{-2}$, the intermediate value of $sin\theta_\chi = 0.5$ and $m_{h^0} = 85\, GeV$ ($m_{A^0} = 90\, GeV$). A_{CP} is at the order of the magnitude of $10^{-3}-10^{-2}$ and slightly larger for $C_7^{eff} < 0$ compared to the one for $C_7^{eff} > 0$. Fig 8 (9) represents the $sin\, \theta_\chi$ dependence of $A_{CP}(t \rightarrow bWh^0(A^0))$ for $|\bar{\xi}^{D}_{N,bb}| = 30\, m_b$, $|\chi| = 10^{-2}$, the intermediate value of $sin\theta_{bb} = 0.5$ and $m_{h^0} = 85\, GeV$ ($m_{A^0} = 90\, GeV$). The behavior of A_{CP} is similar to the one obtained in Fig. 6 (7). As shown in these figures, A_{CP} is a mesurable quantity, which gives strong clues about the possible physics beyond the SM.

Now we will summarize our results:

- The BR of the process $t \rightarrow bWh^0(A^0)$ is at the order of 10^{-6} (10^{-8}) in the model III and it can be measured in the future experiments. This ensures a crucial test for the new physics beyond the SM.

- The BR is sensitive to $\bar{\xi}^{D}_{N,bb}$ and the mass value m_{h^0} (m_{A^0}). This is important in the prediction of the lower limit of the mass $m_{h^0}(m_{A^0})$ with the possible future experimental measurement of the process under consideration.

- A_{CP} is at the order of the magnitude of 10^{-2} for the intermeditate values of $sin\, \theta_{bb}$ and and $sin\, \theta_\chi$. This a mesurable quantity, which gives a strong clue about the possible physics beyond the SM and also more beyond.

Therefore, the experimental investigation of the process $t \rightarrow bWh^0(A^0)$ will be effective for understanding the physics beyond the SM.

4 Acknowledgement

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References

[1] G.Mahlon and S.Parke, *Phys. Lett.* **B347** (1995) 394; E. Jenkins, *Phys. Rev.* **D56** (1997) 458; D. Atwood and M. Sher, *Phys. Lett.* **B411** (1997) 306.

[2] G.Eilam, J.L.Hewett and A.Soni, *Phys. Rev.* **D44** (1991) 1473, erratum *Phys. Rev.* **D59** 039901 (1999).

[3] C.S.Li, R.J.Oakes and J.M.Yang, *Phys. Rev.* **D49** (1994) 293; J.M.Yang and C.S.Li, *Phys. Rev.* **D49** (1994) 3412; G.Couture, C.Hamzaoui and H.König, *Phys. Rev.* **D52** (1995) 171; J.L.Lopez, D.V.Nanopoulos and R.Rangarajan, *Phys. Rev.* **D56** (1997) 3100; G.Couture, M.Frank and H.König, *Phys. Rev.* **D56** (1997) 4213; G.M.de Divitiis, R.Petronzio, L.Silvestrini, *Nucl. Phys.* **B504** (1997) 45.

[4] C. Yue, G. Lu, G. Liu and Q. Xu, *Phys. Rev.* **D64** (1995) 095004; T.Han, R.D.Peccei, and X.Zhang, *Nucl. Phys.* **B454** (1995) 527; T.Han, R.D.Peccei, and X.Zhang, *Nucl. Phys.* **B454** (1995) 527; T.Han, K.Whisnant, B.-L.Young, and X.Zhang, *Phys. Rev.* **D55** (1997) 7241; *Phys. Lett.* **B385** (1996) 311; M.Hosch, K.Whisnant, and B.-L.Young, *Phys. Rev.* **D56** (1997) 5725; E. Malkawi and T. Tait, *Phys. Rev.* **D54** (1996) 5758; T. Tait and C.P. Yuan, *Phys. Rev.* **D55** (1997) 7300; T. Han, M. Hosch, K. Whisnant, B.-L. Young and X. Zhang, *Phys. Rev.* **D58** (1998) 073008; F. del Aguila and J.A. Aguilar-Saavedra, *Phys. Lett.* **B462** (1999) 310; J. L. Diaz-Cruz, M. A. Perez, G. Tavares-Velasco,J. J. Toscano, *Phys. Rev.* **D60** (1999) 115014; F. del Aguila and J.A. Aguilar-Saavedra, *Nucl. Phys.* **B576** (2000) 56; C. Yue, G. Lu, Q.Xu, *Phys. Lett.* **B508** (2001) 290.

[5] W.S.Hou, *Phys. Lett.* **B296** (1992) 179; K.Agashe, M.Graesser, *Phys. Rev.* **D54** (1996) 4445; M.Hosch, K.Whisnant, B.L.Young, *Phys. Rev.* **D56** (1997) 5725; J.Guasch, hep-ph/9710267; L.T.Handoko and J.Hashida, *Phys. Rev.* **D58** (1998) 094008.

[6] G.Eilam, B.Haeri and A.Soni, Phys. Rev. D41 (1990) 875.

[7] B. Mele, S. Petrarca and A. Soddu, *Phys. Lett.* **B435**, (1998) 401.

[8] T. Han and Jing Jiang, B. Mele, *Phys. Lett.* **B516**, (2001) 337.

[9] E. Iltan, *Phys. Rev.* **D65**, (2002) 075017.

[10] E. Iltan, I. Turan *Phys. Rev.* hep-ph/0207087.

[11] C. Yue, G. Lu, G. Liu, Q. Xu, *Phys. Rev.* **D64**, 095004 (2001) .

[12] A. Denner, A. H. Hoang, *Nucl. Phys.* **B397**, (1993) 483; T. Hasuike, T. Hattori, T. HayashiS. Wakaizumi, *Z. Phys.* **C76** (1997) 127. (2002) 483;

[13] E. Jenkins, *Phys. Rev.* **D56**, (1997) 456; J. L. D. Cruz, D. A. L. Falcon, *Phys. Rev.* **D61**, 095004 (2000) 051701; G. Alterelli, L. Conti, V. Lubicz, *Phys. Lett.* **B502**, (2001) 125.

[14] T. M.Aliev, E. Iltan, *J. Phys.* **G25** (1999) 989.

[15] S. Chen, et. al., CLEO Collaboration, *Phys. Rev. Lett.* **87** (2001) 251807.

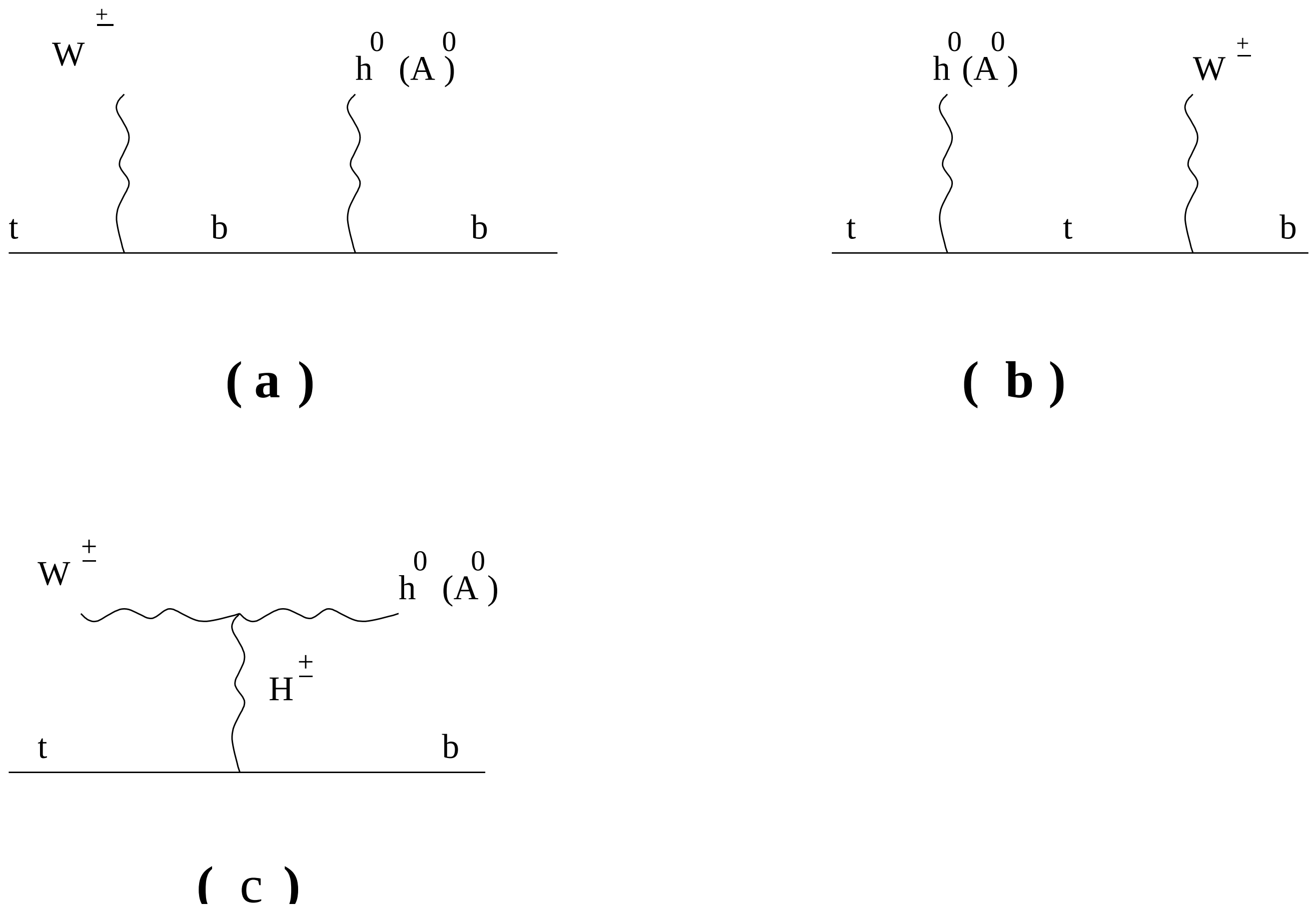

Figure 1: The diagrams contribute to the decay $t \to bWh^0(A^0)$.

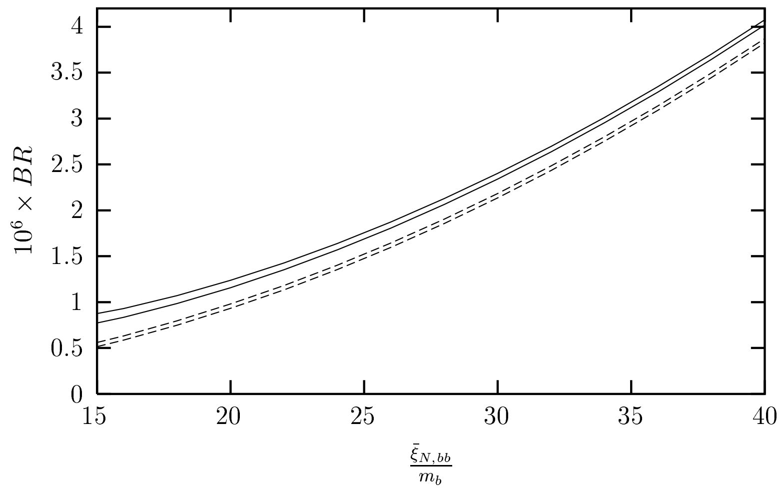

Figure 2: $BR(t \to bWh^0)$ as a function of $\frac{\bar{\xi}^D_{N,bb}}{m_b}$ for $m_{H^\pm} = 400\,GeV$, $m_{h^0} = 85\,GeV$. Here the BR is restricted in the region bounded by solid lines for $C_7^{eff} > 0$ and by dashed lines for $C_7^{eff} < 0$.

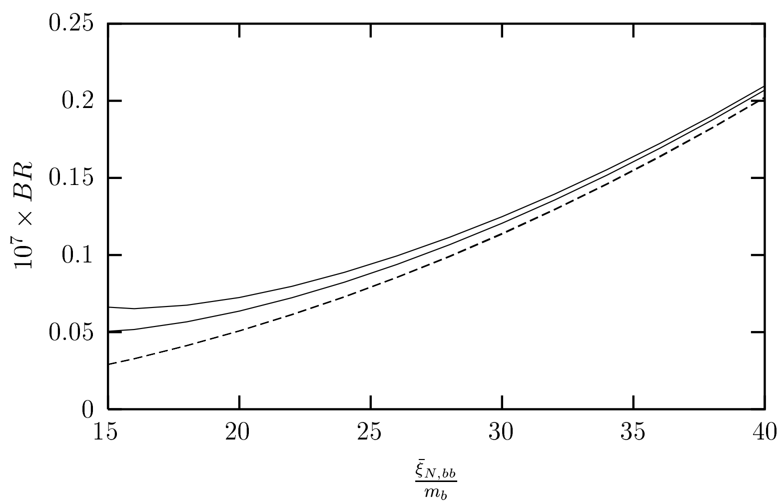

Figure 3: The same as Fig. 2 but for the decay $BR(t \to bWA^0)$.

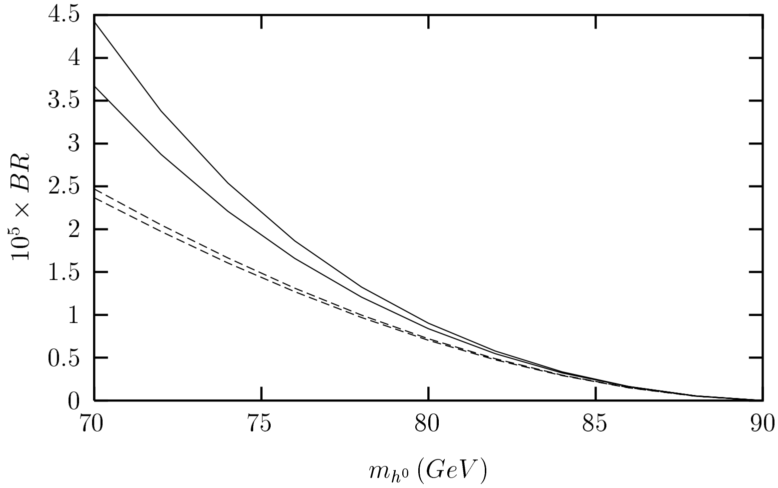

Figure 4: $BR(t \rightarrow bWh^0)$ as a function of m_{h^0} for $\bar{\xi}^D_{N,bb} = 30\, m_b$, $m_{H^\pm} = 400\, GeV$. Here the BR is restricted in the region bounded by solid lines for $C_7^{eff} > 0$ and by dashed lines for $C_7^{eff} < 0$.

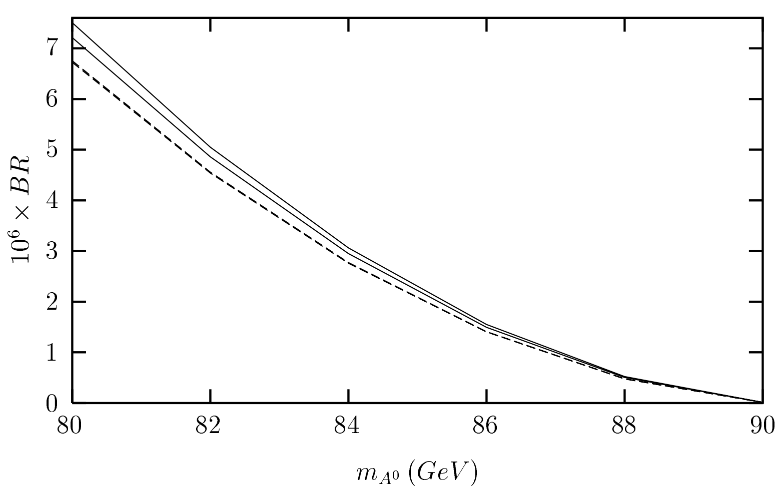

Figure 5: The same as Fig. 4 but for the decay $BR(t \rightarrow bWA^0)$.

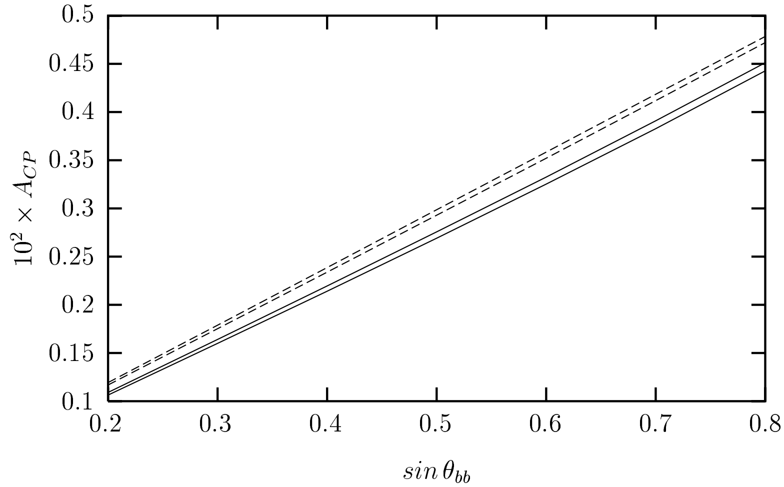

Figure 6: $A_{CP}(t \to bWh^0)$ as a function of $sin\theta_{bb}$ for $|\bar{\xi}^D_{N,bb}| = 30\, m_b$, $m_{H^\pm} = 400\, GeV$, $|\chi| = 10^{-2}$, $sin\theta_\chi = 0.5$. Here the A_{CP} is restricted in the region bounded by solid lines for $C_7^{eff} > 0$ and by dashed lines for $C_7^{eff} < 0$.

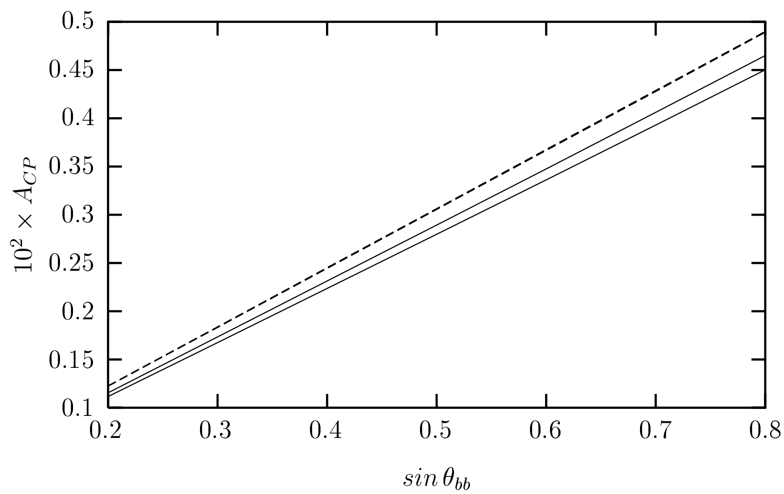

Figure 7: The same as Fig. 6 but for the decay $A_{CP}(t \to bWA^0)$.

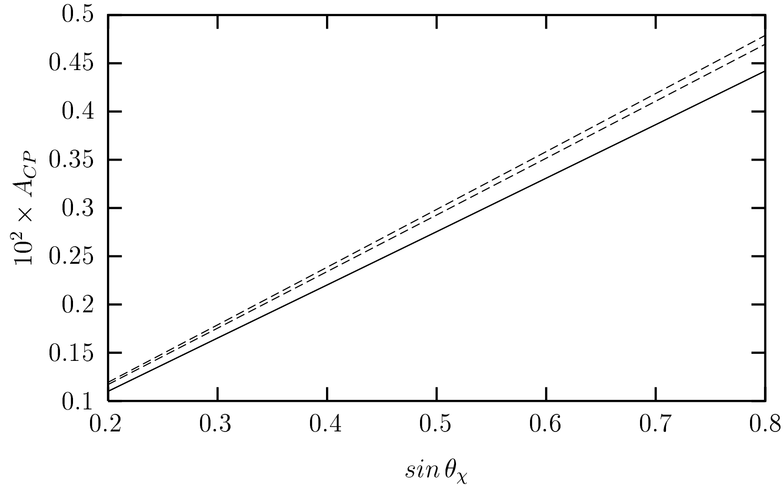

Figure 8: $A_{CP}(t \rightarrow bWh^0)$ as a function of $sin\theta_\chi$ for $|\bar{\xi}^D_{N,bb}| = 30\, m_b$, $m_{H^\pm} = 400\, GeV$, $|\chi| = 10^{-2}$, $sin\theta_{bb} = 0.5$. Here the A_{CP} is restricted in the region bounded by solid lines for $C_7^{eff} > 0$ and by dashed lines for $C_7^{eff} < 0$.

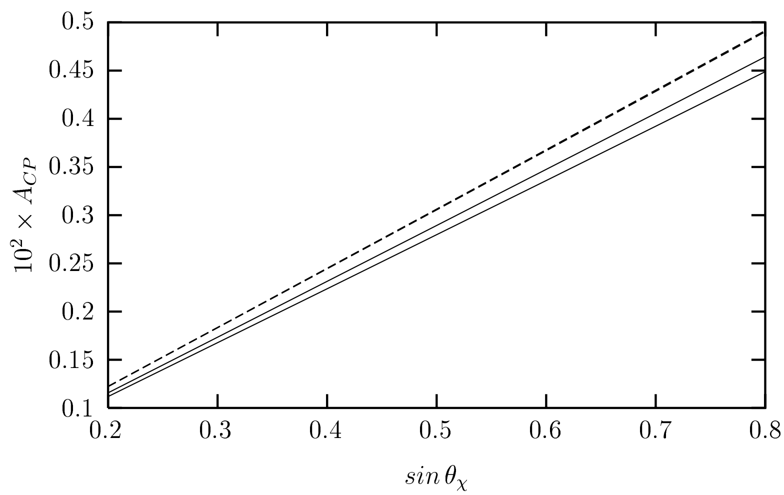

Figure 9: The same as Fig. 8 but for the decay $A_{CP}(t \rightarrow bWA^0)$.